Measurement of residual stresses in a dissimilar metal welded pipe

Conference or Workshop Item

Measurement of Residual Stresses in a Dissimilar Metal Welded Pipe by Neutron Diffraction

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Introduction

Nickel-based weld filler materials are used to join ferritic and stainless steel components in the primary piping system of pressurized water reactors (PWR) in nuclear power plants. Dissimilar metal weld (DMW) joints of this kind contain several material interfaces, involve multiple fabrication steps and often have a complex geometry. Stress corrosion cracking (SCC) has been observed at DMWs in many operating PWRs throughout the world. SCC is driven by the presence of tensile residual stress given a susceptible microstructure and adverse local chemistry. It is important to assess the distribution of residual stress in DMWs which is difficult to characterise with high certainty either by computational mechanics or measurement.

A new narrow-gap DMW using a corrosion resistant filler material (Alloy 52) has been designed by the French nuclear power plant constructor AREVA NP. A mock-up (designated MC1) of this new weld design has been fabricated and the residual stresses were measured by deep hole drilling (DHD) and by neutron diffraction using the high flux reactor at JRC-Petten [1] both before and after a post weld heat treatment (PWHT) at 600°C for 1h.

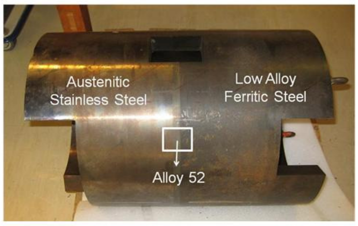

Fig. 1: Dissimilar metal weld mock-up (MC1) outer radius = 352mm, thickness = 40 mm

Here we report new neutron diffraction measurements made on mock-up MC1 after PWHT using ENGIN-X [2], the time-of-flight neutron diffractometer at the ISIS Facility in the UK. In particular we focus on the strategy adopted to deal with the challenges of measuring this component including the section thickness (40 mm) and the issue of obtaining reliable stress-free reference measurements.

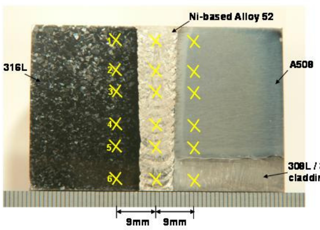

Fig. 2: Polished and etched cross-section of mock-up (MC1) DMW weld showing different materials, Alloy 52 weld beads and neutron diffraction measurement locations

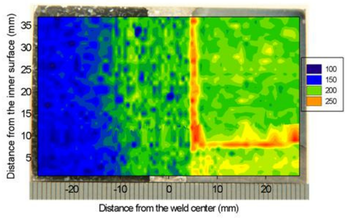

Fig. 3: Vickers-hardness map of mock-up MC1 cross-section after PWHT

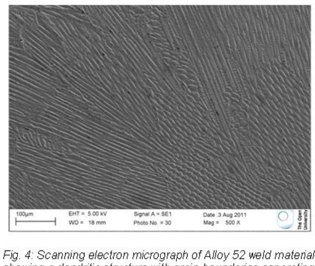

Fig. 4: Scanning electron micrograph of Alloy 52 weld material showing a dendritic structure with grain boundaries separating colonies of dendrites with different orientations

Ni	Cr	Fe	Mn	Si	Ti	C
59.15	29.12	10.06	0.25	0.13	0.51	0.023

Nb+Ta	Mo	Cu	Co	Al	S	Others
<0.01	0.01	0.01	0.007	0.71	<0.001	<0.50

Table 1: Chemical composition of Alloy 52

Methodology

Strain Scanning Simulation Software (SScanSS) [3] was used to design and control the experiment to high positional accuracy. Because the specimen thickness (40 mm) gave neutron path-lengths at the operational limit of the ENGIN-X diffractometer, non-standard neutron optics were used in order to increase the flux as illustrated in the Fig. 5. The penalty of increased beam divergence was minimised by placing the downstream slits as close as possible to the sample. A large gauge volume of 4×8×6 mm^3 was used for the measurements to reduce the count time for the longest path-length to about 1 hour. The axial, radial and hoop strain components were measured at six points along three lines in four different materials as shown in Fig. 2. The worst spectrum for the longest path-length in the Alloy 52 material is shown in Fig. 6.

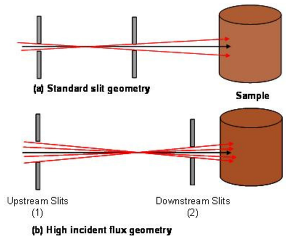

Fig. 5: Schematic showing how the neutron beam line optics were adjusted to increase the flux

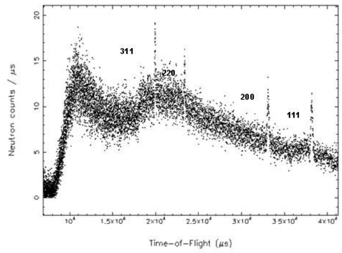

Fig. 6: Diffraction spectrum for the longest path length hoop component in Alloy 52

Stress-free reference measurements were obtained in three orthogonal directions (axial, radial and hoop) by slowly rotating cuboids (9×9×8) mm^3 extracted from the PWHT weldment) using a gauge volume of (4×4×4) mm^3. The cuboids were electro-discharge machined from a plug (60 mm diameter) of material spanning the DMW removed from a circumferential position remote from that measured by neutron diffraction. The a_0 value thus used for stress calculations is the average of the three directions measured and is not position sensitive. The rotating strategy was adopted because previous direction dependent measurements on the weldment cuboids showed large variations in measured a_0 of 450, 400 and 600 micro-strains in austenite, ferrite and alloy 52 respectively.

Results

Following Rietveld analysis [4] of the diffraction spectra, residual strains in three orthogonal directions were computed for the three measurement lines using the measured a_0 values. Stresses were computed in the usual way assuming isotropic material behaviour and bulk elastic constants (E = 172 GPa and v = 0.29 for Alloy 52). The distributions of residual stresses in three orthogonal along the centre-line of the Alloy 52 weld are shown in Figure 7. The largest tensile stress (264 MPa) was in the hoop direction close to the outer surface.

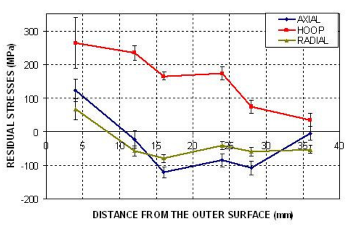

Fig. 7: Measured stresses at the centre-line of the Alloy 52 weld using ENGIN-X, the error bars include the uncertainty in the stress- free lattice parameter measurements

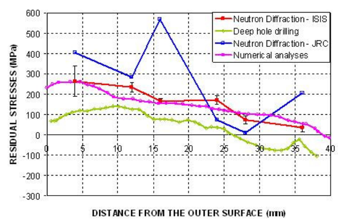

Fig. 8: Hoop stresses on the centre-line of the Alloy-52 weld; comparison of ENGIN-X measurements with a computation prediction and other measurements [5]

The ENGIN-X hoop stresses at the weld centre-line are compared with independent neutron measurements undertaken at JRC-Petten, DHD measurements and a weld computation mechanics prediction [5] in Fig. 8. All the data show a similar trend, with high tensile stresses near the outer surface falling to near zero stress close to the inner surface. The ENGIN-X measurements are generally more tensile than the deep hole data. No evidence of high stress at 16 mm from the outer surface was found which suggests that the JRC data at this point was an outlier. The finite element predicted hoop stress profile is in reasonable agreement with the present ENGIN-X results.

Conclusion

Residual stresses in a 40 mm thick dissimilar metal pipe weld have been successfully measured using the ENGIN-X instrument at the ISIS Facility. The measurements were achieved by opening the upstream slits to increase the neutron flux, using a large gauge volume and reducing the uncertainty in stress-free lattice parameter measurements by slowly spinning extracted cubes of weldment materials. The origins of the large uncertainties in "unspun" stress-free reference measurements are being investigated.

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